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Field Calibration of Reference Reflectance Panels

RAY D. JACKSON and M. SUSAN MORAN

U. S. Department of Agriculture, Agricultural Research Service, U. S. Water Conservation Laboratory, Phoenix, Arizona 85040

PHILIP N. SLATER and STUART F. BIGGAR

Optical Sciences Center, University of Arizona, Tucson, Arizona 85721

The measurement of radiation reflected from a surface must be accompanied by a near-simultaneous measurement of radiation reflected from a reference panel in order to calculate a bidirectional reflectance factor for the surface. Adequate calibration of the reference panel is necessary to assure valid reflectance-factor data. A procedure is described by which a reference panel can be calibrated with the sun as the irradiance source, with the component due to diffuse flux from the atmosphere subtracted from the total irradiance. Furthermore, the radiometer that is used for field measurements is also used as the calibration instrument. The reference panels are compared with a pressed polytetrafluoroethylene (halon) standard. The advantages of this procedure over conventional laboratory calibration methods are, first, that the irradiance and viewing geometry is the same as is used in field measurements and, second, that the needed equipment is available, or can be constructed, at most field research laboratories, including the press necessary to prepare the halon standard. A disadvantage of the method is that cloud-free sky conditions are required during the measurement period. The accuracy of the method is estimated to be 1%. Calibration results are given for four reference panels.

Introduction

Remote sensing of the earth's surface consists of measuring the spectral radiance reflected from the surface, followed by the interpretation of the measured data in terms of physical features of the surface. The radiance received by a remote sensor is a function of the continuously varying incident solar irradiance, atmospheric conditions, and the reflectance properties of the surface. Because of the time dependence of radiance data, bidirectional reflectance factors are frequently calculated to facilitate comparison of information concerning surface features from multitemporal data.

A bidirectional-reflectance factor can be defined as the ratio of the flux reflected by a sample surface to that which would be reflected into the same beam geometry by a lossless, perfectly diffuse (lambertian) surface that is identically irradiated (Nicodemus et al., 1977; Robinson and Biehl, 1979). Because a perfect lambertian surface cannot be achieved, panels used as reference reflectance standards must be adequately calibrated to account for their non-lambertian properties (Robinson and Biehl, 1979; Kimes and Kirchner, 1982). By calibration, the non-lambertian properties of a reference panel can be embodied in a bidirectional-reflectance factor specific to the panel. With a calibrated panel, the radiant flux from a perfectly diffuse surface can be approximated.

Reference surfaces intended for field use are generally constructed by coating an aluminum panel with a highly reflecting substance such as barium sulfate ($BaSO_4$) or polytetrafluoroethylene (fre-

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quently referred to as halon, TFE, or PTFE) (Robinson and Biehl, 1979; Schutt et al., 1981). Their construction requires considerable skill and attention to detail. Two panels constructed by the same person at the same time may differ in their reflectance properties. Furthermore, reflectance properties of panels change with use. Reference panels are generally not commercially available; hence, most users are forced to construct their own. Consequently, panel calibration becomes a factor of considerable importance when bidirectional reflectance-factor measurements are to be compared for different times and different surfaces.

As with panel construction, panel calibration services are difficult to obtain. Thus, researchers at field stations may be able to construct a reference panel, but may not have the resources to calibrate it adequately. Furthermore, if a laboratory can be located that will calibrate a panel, the instruments used will not be the same as used in the field. As an example, a laboratory calibration procedure may use light from a standard tungsten lamp at a known distance and incident normally to the panel. The reflected beam may be measured by a radiometer or a spectrophotometer having a 1° field of view, and a spectral bandwidth of a few nanometers. The panel may subsequently be used in the field with the sun and sky as light sources and a relatively wide-band radiometer (with say, the Thematic Mapper bands) having a 15° field of view, as the measuring instrument. The precise laboratory calibration will not apply exactly in the field under these different measurement conditions.

The calibration of a reference-reflectance panel consists of determining the functional relationship of the reflectance factor to the view/irradiance angle, and the comparison of the radiance from the panel to the radiance from a standard surface for a specified view/irradiance angle combination. The standard surface should be a National Bureau of Standards Certified Standard Reference Material, or a surface of pressed $BaSO_4$ or pressed halon constructed according to NBS specifications (Weidner and Hsia, 1981).

Our objective is to describe how reference reflectance panels can be calibrated using the sun as the radiation source and a pressed-halon standard (constructed locally), with the same radiometer that is to be used subsequently for field reflectance-factor measurements as the measuring instrument.

Reflectance-Factor Relationships and Nomenclature

The bidirectional-reflectance factor $R(\theta_i, \phi_i; \theta_r, \phi_r)$ is specified by the angles of the incident (i) and reflected (r) beams, and the zenithal (θ) and azimuthal (ϕ) directions (Robinson and Biehl, 1979). For many reflectance-factor measurements of surfaces and reference panels, the radiometers are directed normal to the surface (zero view angle). Reference panels are generally considered azimuthally isotropic. In this paper, we will adopt the nomenclature of Hsia and Weidner (1981), and define the bidirectional-reflectance factor as $R(0°/\theta)$, and, in accordance with Hsia and Weidner, call the term the directional/directional reflectance factor, with the view direction set at 0°. Because of its incidence-angle dependence, $R(0°/\theta)$ is significantly affected by the non-lambertian properties of reference panels.

For the case of irradiance from a hemisphere being reflected from a panel to a sensor at nadir (or the opposite configuration), we have the directional/hemispherical reflectance factor, $R(\theta/h)$. The factor $R(\theta/h)$ is considerably less sensitive to incidence-angle changes than is $R(0°/\theta)$. Data of Weidner and Hsia (1981) indicate that $R(\theta/h)$ changes less than 0.3% for the range $0° < \theta_i < 75°$, for wavelengths from 0.45 to 0.75 μm. For practical purposes, $R(\theta°/h) = R(0°/h)$. This term can be measured with an integrating-sphere spectrophotometer system such as that described by Zerlaut and Anderson (1981). In their system, monochromatic light is directed toward a target at an angle of 20°. Little error is involved in equating $R(0°/h)$ and $R(20°/h)$.

According to the Helmholtz reciprocity principle, $R(0°/\theta) = R(\theta/0°)$, and $R(0°/h) = R(h/0°)$. Thus, the view and irradiance angles can be interchanged.

For azimuthally uniform reference panels, the relationship between $R(0°/\theta)$ and $R(0°/h)$ is

$$R(0°/h) = 2\int_0^{\pi/2} R(0°/\theta)\cos\theta\sin\theta\, d\theta. \tag{1}$$

When $R(0°/\theta)$ is approximated by a polynomial in θ, Eq. (1) can be integrated and the result written as a summation, i. e.,

$$R(0°/h) = 2\sum_{j=0}^{n} b_j I_j, \tag{2}$$

where b_j are coefficients of the polynomial and $I_j = \int_0^{\pi/2}\theta^j \sin\theta\cos\theta\, d\theta$, with values of the integrals (for $j = 0$–3) being, $I_0 = 0.50000$, $I_1 = 0.39270$, $I_2 = 0.36685$, $I_3 = 0.37990$ (Hsia and Weidner, 1981).

Since $R(0°/\theta)$ is to be evaluated, it must be expressed in terms of measurable quantities. The radiance reflected from a surface is proportional to the reflectance factor of the surface. Futhermore, the radiance received by a radiometer having a linear response, and viewing the surface from above, is proportional to the voltage response (V) of the radiometer. Thus,

$$R(0°/\theta) = AV/\cos\theta_i = AV(0°/\theta). \tag{3}$$

Here $A = K/E$, where K includes the calibration constant of the radiometer and E is the direct irradiance on the panel. Dividing the voltage response V by $\cos\theta_i$ normalizes the response to that which would obtain at zero incidence angle.

Substituting Eq. (3) into Eq. (1) yields

$$R(0°/h) = 2A\int_0^{\pi/2} V(0°/\theta)\cos\theta\sin\theta\, d\theta. \tag{4}$$

If $V(0°/\theta)$ is approximated by a polynomial in θ, then Eq. (2) becomes

$$R(0°/h) = 2A\sum_{j=0}^{n} b_j I_j, \tag{5}$$

where b_j are now the coefficients of the polynomial that relates the voltage response to θ.

$V(0°/\theta)$ can be evaluated with a goniometer and, if $R(0°/h)$ is known (its evaluation is discussed in the following section), A is calculated using Eq. (5). The directional/directional reflectance factor is calculated as a function of solar zenith angle using Eq. (3).

Experimental Methods and Procedures

The evaluation of $R(0°/\theta)$ requires a radiometer, a reflectance standard of sufficient size to be used in field measurements, and a goniometer by which a reference panel can be positioned at a known incidence angle from the sun. The majority of the measurements reported here were made with a Barnes Modular Multispectral Radiometer (MMR).[1] This radiometer has eight bands, seven of which are similar to the seven Thematic Mapper (TM) bands. MMR bands 1–4 and 7 are similar to TM bands 1–4 and 7. MMR band 5 (1.15–1.3 μm) has no TM counterpart. MMR band 6 is similar to TM band 5. Nominal wavelength intervals for the MMR bands are: 1) 0.45–0.52 μm; 2) 0.52–0.60 μm; 3) 0.63–0.69 μm; 4) 0.76–0.90 μm; 5) 1.15–1.30 μm; 6) 1.55–1.75 μm; 7) 2.05–2.30 μm.

Pressed-halon standard

The National Bureau of Standards developed a procedure for the preparation of a standard of diffuse reflectance by pressing polytetrafluoroethylene (halon) powder to a prescribed density (Weidner and Hsia, 1981). The procedure requires no specialized equipment or materials other than commercially available halon powder.

We constructed a $55.8 \times 55.8 \times 1$ cm pressed-halon standard following the procedures outlined by Weidner and Hsia (1981) with the exception of size, our standard being considerably larger than those constructed for laboratory use. A $55.8 \times 55.8 \times 2.54$ cm iron press plate was capped with a 0.32 cm thick stainless-steel plate that had been sandblasted to roughen the surface. Halon powder was prepared in a stainless steel blender and 3.12 kg were placed into the holder (with 4 cm side extensions). The powder was pressed to a height of 1 cm, yielding an average density of 1.0 $g\,cm^{-3}$.

Weidner et al. (1985) reported the results of two experiments in which different laboratories prepared samples of pressed halon and returned them to the NBS for analysis. They concluded that, with proper preparation, standards could be made that are reproducible to within ± 0.005 in reflectance for the 0.3–2.0-μm spectral interval and ± 0.01 for the 2.0–2.5-μm interval. The greatest differences were from samples that deviated considerably from the prescribed density of 1.0 $g\,cm^{-3}$.

$R(0°/h;\lambda)$ data for pressed halon over the spectral range 0.2–2.5 μm are given in Fig. 1 (from Table 3, Weidner and Hsia, 1981). Values of $R(0°/h)_i$ for seven MMR bandwidths were obtained by integrating the product of the radiometer response function $\mathrm{RRF}(\lambda)$ and $R(0°/h;\lambda)$ divided by the integral of the response function, over the wavelength interval for band i, that is, $R(0°/h)_i = \int \mathrm{RRF}(\lambda) \cdot R(0°/h;\lambda)\, d\lambda / \int \mathrm{RRF}(\lambda)\, d\lambda$. Subsequent use of the term $R(0°/h)$ will signify the integrated value over the wavelength interval.

For MMR bands 1–4, $R(0°/h) = 0.994$, and for bands 5–7, $R(0°/h) = 0.993$, 0.991, and 0.971, respectively, obtained from the data of Weidner and Hsia (1981). An advantage of the fact that $R(0°/h;\lambda)$ for pressed halon changes very little with wavelength is that the radiometer response functions do not need

[1] Trade names and company names are included for the convenience of the reader and imply no endorsement by the U.S. Department of Agriculture or the University of Arizona.

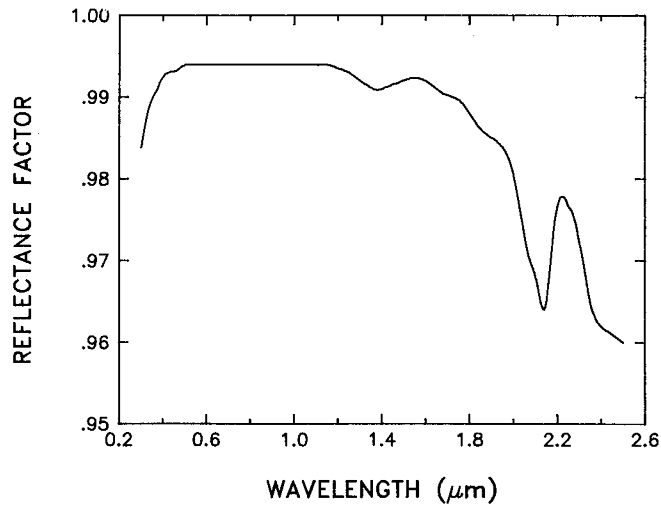

FIGURE 1. Reflectance spectra for pressed polytetrafluoroethylene powder (after Weidner and Hsia, 1981).

to be accurately known to obtain $R(0°/h)$ for each wavelength interval of the radiometer.

Field goniometer

The first step in obtaining $R(0°/\theta)$ for a reference panel is to evaluate its non-lambertian properties over a range of sun/panel incidence angles. A field goniometer and its operation are described in the following sections

Apparatus. The field goniometer consists of a table (to hold the reference panel) fastened to a frame that allows zenithal movement of the table. In turn, the frame is fastened to a wheel assembly that turns azimuthally. An arm extends from the back of the table upward about 1 m, then forward towards the center of the table. A radiometer is positioned at the end of the arm about 1 m above the table with the view angle always held normal to the reference panel. The table can hold reference panels up to 1.2 m on a side.

A particular incidence angle for the solar beam striking the panel is obtained by setting a pointer to a particular angle on a 90° protractor. The pointer is parallel to a tube that allows a beam of sunlight to pass through a small (2 mm) hole in the forward end of the tube. The table is moved in zenith and azimuth until the sunbeam is aligned with crossed lines etched on a clear plastic plate on the rear of the tube. The crossed lines and the sunbeam are observed on an adjustable metal plate held a few cm from the end of the tube. When aligned, the incidence angle of the solar beam on the panel is known.

Procedure. In practice, the pointer is first set at 15°. Incidence angles less than 15° cannot be obtained because the radiometer then shades part of the panel, thus negating the measurement. After adjusting the table until the sunlight passing through the tube is aligned with the crossed lines, a measurement sequence (to be discussed in the subsequent paragraph) is initiated. The pointer is then set to the next desired angle and the measurement sequence repeated. Measurements are made in approximately 10°

increments to about 75°. Beyond 75° the required accuracy of the incidence angle exceeds the capability of the apparatus. After completing the 75° measurement, the sequence is immediately repeated but in reverse order, a necessary procedure to minimize the effect of changing solar irradiance during the course of the measurements.

For making directional–directional reflectance-factor measurements, we are concerned only with the direct solar beam and need to remove the diffuse sky radiation from the data. This is accomplished by alternately shading and exposing the panel to the total sun–sky irradiance, and subtracting the diffuse (shaded) component from the total. To shade the panel, the direct beam is blocked by an opaque plate slightly larger than the reference panel, held on the end of a 3.5-m pole. This obstructs a 0.1-sr solid angle, or about 1.6% of the hemisphere above the panel. Because of the constantly changing solar angle, two shaded measurements are made bracketing a sunlit measurement. The two diffuse measurements are averaged and subtracted from the sunlit measurement. The measurement time is recorded as the time of the sunlit measurement.

To partially compensate for the small portion (about 1.6%) of the sky that is blocked by the shading plate, the plate is held upright but just to the side during the sunlit measurements, blocking approximately the same portion of the sky. Because diffuse radiation is greatest near the sun, this compensation is only partial.

The voltage output from each channel of the radiometer, recorded by a portable data acquisition system, decreases with increasing incidence angle. The purpose of repeating the measurements after reaching the largest incidence angle is to minimize the effect of changing sun angle. Figure 2 shows a plot of output voltage for one channel as a function of time.

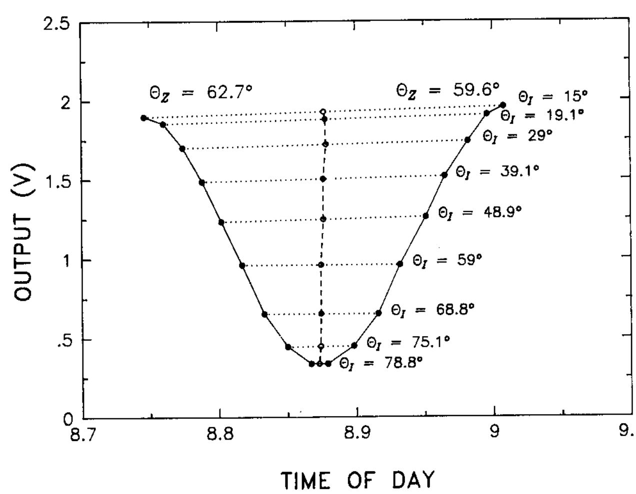

FIGURE 2. Radiometer response at nine incidence angles as a function of time (h). The open circles result from averaging the time and voltage response at each incidence angle. When the dashed lines connecting the open circles are straight and vertical, the data can be considered to be taken at a constant solar irradiance.

The starting and ending solar zenith angles are given in the upper left and upper right portions of the graph. The incidence angles are shown next to the ascending data points on the right. The open circles represent the average of the two voltage readings (total–diffuse) plotted at the average time for the measurements. The dashed lines connecting the data points are all nearly vertical, which demonstrates that the average of the two measurements corresponds to very nearly the same solar zenith angle for all incidence angles. Thus, the requirement that the irradiance of the panel during the course of the measurements be constant can be sufficiently met with this procedure.

To evaluate $V(0°/\theta)$, the data represented by the open circles in Fig. 2 were divided by the cosine of the angle of incidence for each measurement, and normalized by dividing by the value at the lowest incidence angle (15°). Next, a third-order polynomial was fit to each set of data, yielding coefficients that can be expressed as

$$V(0°/\theta) = \sum_{j=0}^{3} b_j \theta^j. \tag{6}$$

An example of the result is plotted in Fig. 3 for a $BaSO_4$ panel. The symbols represent measured data and the lines the polynomial fit to the data. In this example, the correlation coefficients for the seven bands were all between 0.9965 and 0.9980.

A calibration run consisted of measuring $V(0°/\theta)_p$ for each panel and $V(0°/\theta)_{std}$ for the pressed-halon standard, using the goniometer. About 15 min were required to obtain data at eight or nine incidence angles for both increasing and decreasing angles (Fig. 2). After completion of the $V(0°/\theta)$ measurements, the voltage-response ratio for each panel to the standard (V_p/V_{std}) was de-

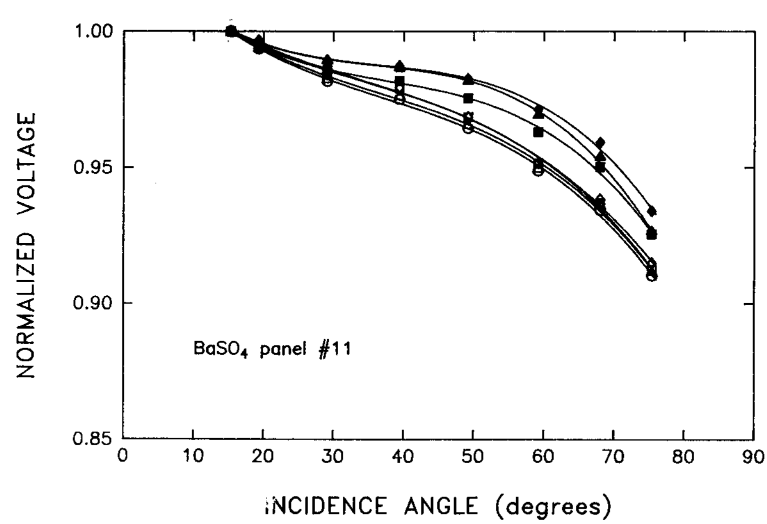

FIGURE 3. Voltage response divided by cos θ_i and normalized by the response at $\theta_i = 15°$. Lines represent a statistical fit of a third order polynomial. Symbols indicate data for 7 MMR bands: (□) band 1; (◇) band 2; (△) band 3; (○) band 4; (■) band 5; (◆) band 6; (▲) band 7.

termined. This was accomplished by fixing the goniometer table in a horizontal position with the radiometer viewing from zero to zenith. A panel was placed on the table and three radiometer readings recorded. All other panels, and the pressed-halon standard, were sequentially (in predetermined order) placed on the table and the radiometer response recorded. After the last measurement, the sequence was repeated, but in reverse order. The two sets of six readings per panel were averaged, thus minimizing the effect of changing solar irradiance in the same manner as were the goniometer measurements of $V(0°/\theta)$ (Fig. 2). The average solar zenith angle during the measurement was recorded. The ratio of the voltage response for a particular panel to the voltage response of the halon standard (V_p/V_{std}) was formed for each panel.

Using published values of $R(0°/h)$ for the halon standard (Weidner and Hsia, 1981) and the measured $V(0°/\theta)_{std}$, the value of A for the standard (A_{std}) was obtained from Eq. (5). Then the reflectance factor for the halon standard at the solar zenith angle corresponding to the time that the comparison measurements (V_p/V_{std}) were made was calculated, i. e.,

$$R(0°/\theta_z)_{std} = A_{std} \cdot V(0°/\theta_z)_{std}. \quad (7)$$

The reflectance factor for a panel at the particular θ_z is

$$R(0°/\theta_z)_p = R(0°/\theta_z)_{std} \cdot V_p/V_{std}. \quad (8)$$

Using Eq. (3), the A value for a panel (A_p) is

$$A_p = R(0°/\theta_z)_p/V(0°/\theta_z)_p. \quad (9)$$

With A_p and $V(0°/\theta)_p$ known from the measurements, Eq. (3) can be used to determine $R(0°/\theta)_p$, the directional-directional reflectance factor for the panel.

Reproducibility of Reflectance Measurements

Seven measurements of $V(0°/\theta)$ for the pressed-halon standard were made on three days over a period of a week. Values of A_p were calculated for each measurement set. Using Eq. (3), $R(0°/\theta)$ values were calculated at 1° increments from 15° to 75° for each of the seven measurements. The mean value was calculated for each increment and the maximum difference from the mean plotted as a function of incidence angle (Fig. 4). For incidence angles from 20° to 70°, the range of differences from the mean for the seven measurements was ±0.2%. The differences increased to ±0.5% at the extremes (15° and 75°). These results demonstrate the precision of the method.

The absolute reflectance values of our pressed-halon standard are based on the applicability of the $R(6°/h)$ data of Weidner and Hsia (1981). Two possibilities for error are improper construction of the standard and contamination of the surface. If a standard is to be used in the field, contamination by dust must be expected. We used the standard on three occasions, the last being 2 weeks after it was constructed.

About 4 weeks after construction, the standard was compared with a smaller (10 cm diameter) halon panel constructed at the Optical Sciences Center at the University of Arizona. The smaller panel was pressed 2 days before the comparison. A 1° FOV radiometer alternately

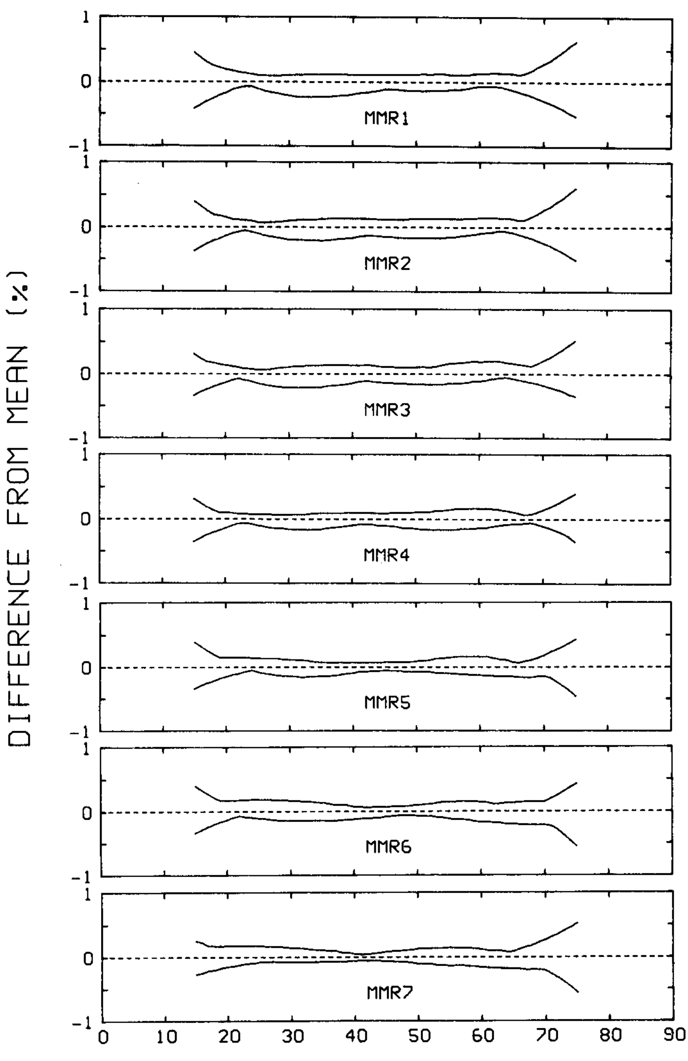

FIGURE 4. Maximum difference from the mean of seven measurements of $R(0°/\theta)$ for a pressed-halon standard.

measured the two halon panels that were illuminated by sunlight. The radiometer filters, of 20 nm bandwidth, were centered on 0.450, 0.500, 0.550, 0.650, 0.750, and 0.850 μm. Ratios of the radiometer readings over the field standard to the freshly pressed small standard are presented in Table 1 for the six wavelength intervals. The greatest difference between the two standards was at 0.450 μm. This difference, 1.01%, decreased with increasing wavelength. At 0.850 μm the difference was 0.1%. These differences are consistent with the fact that dust contamination usually causes a greater decrease in reflectance at the shorter wavelengths than at the longer wavelengths. Since some contamination

TABLE 1 Ratios of Radiometer Readings over the Large Field Halon Standard to the Freshly Pressed Small Standard for Six Wavelengths

WAVELENGTH (μm)	0.450	0.500	0.550	0.650	0.750	0.850
RATIO	0.989	0.992	0.993	0.997	0.998	0.999

undoubtedly occurred during the field exposure, we attribute the difference in reflectance of the two standards to contamination and conclude that the large panel was constructed substantially in line with NBS recommendations and that the $R(0°/h)$ values of Weidner and Hsia (1981) were applicable.

$BaSO_4$ and Painted Halon Panels

Four reference panels, three painted $BaSO_4$ and one painted halon, were calibrated using the procedure described above. Two of the painted $BaSO_4$ panels were constructed at the University of Arizona by the same person at the same time. These panels were numbered 10 and 11 for identification purposes. The third $BaSO_4$ panel (#12) was constructed at Colorado State University. The procedures used in painting the three $BaSO_4$ panels were similar to the procedure developed at the Laboratory for Applications of Remote Sensing, Purdue University, by Robinson and Biehl (1979). The painted halon panel (#3), was constructed at the Goddard Space Flight Center, Greenbelt, MD, using the procedure of Schutt et al. (1981).

Values of $R(0°/\theta)$ for $BaSO_4$ panel #11 for the seven reflective bands of the MMR for incidence angles ranging from 15° to 75° are shown in Fig. 5. Reflectance factors for all seven bands decrease with increasing incidence angle. The blue and green bands (1 and 2) have essentially the same reflectance values, whereas reflectance decreases with increasing wavelength for the remaining five bands. MMR band 7 ($\simeq$ TM band 7) has the lowest reflectance values, being about 0.7.

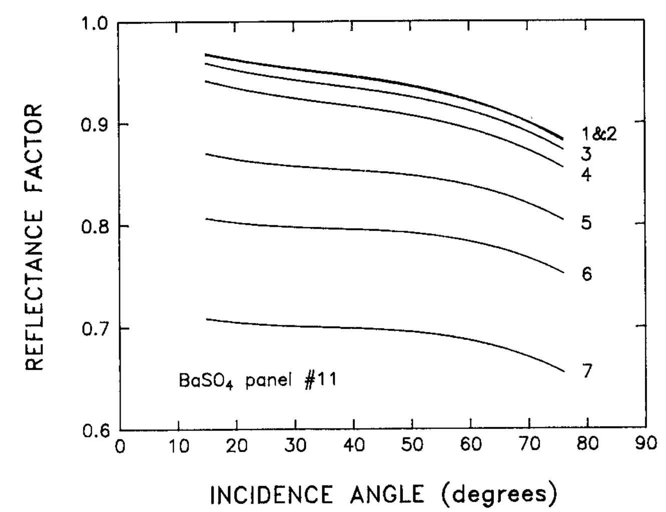

FIGURE 5. Reflectance factor values for a painted $BaSO_4$ panel calibrated with reference to a pressed-halon standard. Numbers at the end of the lines indicate the band number of the MMR radiometer.

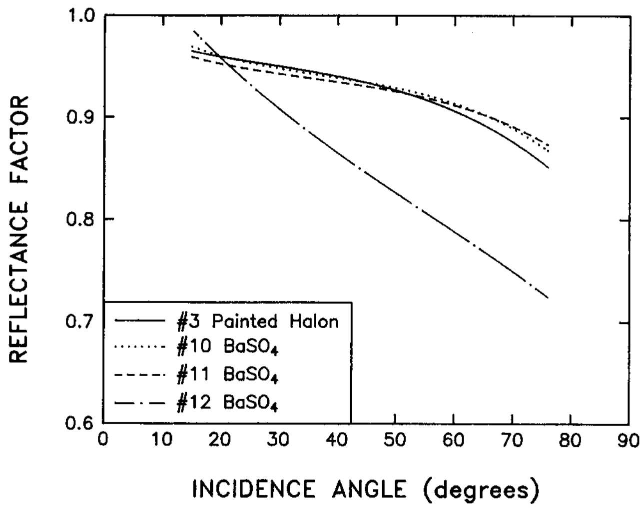

FIGURE 6. Comparison of MMR band 3 (0.63–0.69 μm) reflectance factors for four reference panels.

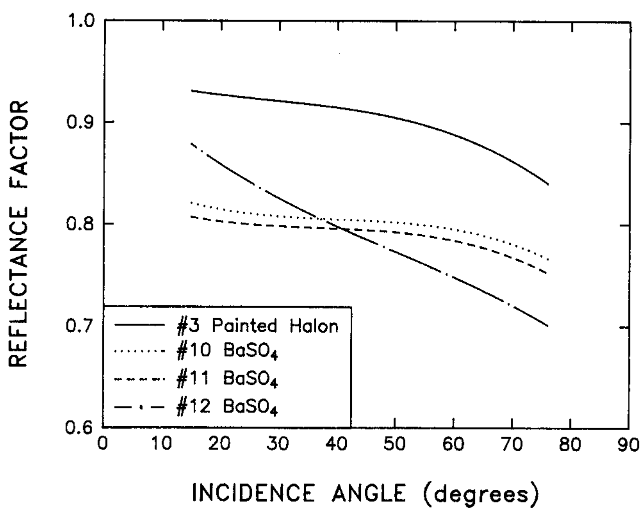

FIGURE 7. Comparison of MMR band 6 (1.55–175 μm) reflectance factors for four reference panels.

MMR band 3 ($\simeq$ TM band 3) reflectance factors for three $BaSO_4$ and a painted halon panel are compared in Fig. 6. $BaSO_4$ panels #10 and #11 are slightly different, with #11 having a lower reflectance than #10 at low incidence angles and higher at the high angles. Reflectance of the painted halon panel (#3) is very close to that of panel #10 at low angles, but falls below values for both #10 and #11 at higher angles. Reflectance values for $BaSO_4$ panel #12 are considerably different than for the other three. They are higher at low angles but decrease rapidly with increasing incidence angles.

A similar comparison between panels, but this time for MMR band 6 ($\simeq$ TM band 5) is shown in Fig. 7. For this band, reflectance values for panels #10 and #11 are distinctly different with #10 being higher than #11 at all incidence angles. Furthermore, the reflectances are near 0.8 for this band whereas they were > 0.9 for band 3. In contrast, the painted halon (#3) reflectances for MMR band 6 decreased only a few percent from those for band 3. $BaSO_4$ panel #12 decreased with increasing angle but not as drastically as for band 3.

Panels #10 and #11 were constructed by the same person at the same time using the same technique, yet reflectance differences are observable. Panel #12, constructed at another location but generally following the same procedure, had drastically different reflectance values. The painted halon panel, although similar to #10 and #11 in band 3, had considerably higher reflectance values at the longer wavelengths. These results clearly demonstrate the need for careful reference-panel calibration.

Cross Calibrations

If a calibrated panel is available, but no field goniometer, calibration of other panels can be accomplished by placing them in relatively close proximity, at the same height above the ground, and alternately placing a radiometer over the panels and recording the response. For a particular sun angle, the reflectance of the calibrated panel can be calculated [Eq. (7)] and the reflectance of the uncalibrated panels calculated by multiplying this reflectance by the ratio of the radiometer voltage response of the uncalibrated to the calibrated panel [Eq. (8)]. If this were done at a number of sun angles, and a polynomial equation fit to the data, a relationship between the reflectance factor and the sun zenith angle for the panel could be obtained. This procedure should yield reasonable calibration equations for each panel. However, if the reference panel had been calibrated using the technique described in this report, i.e., with the diffuse sky radiation subtracted from the total, a shading procedure should be used to minimize the effect of diffuse irradiance on the evaluation of $R(0°/\theta_z)$ for the calibrated panel.

Influence of Diffuse Irradiance

Measurements of reflectance factors of targets in the field are usually made under conditions of total (direct and diffuse) irradiance. The target reflectance factor (R_t) is obtained by ratioing the voltage response of the target and the panel (V_t/V_p) and multiplying by the panel reflectance factor [$R(0°/\theta_z)$]. The direct irradiance strikes the panel at an angle θ_z, for which the solar zenith dependent $R(0°/\theta)$ can be calculated. However, the source of diffuse irradiance is the hemispherical sky above the panel. The nonisotropic nature of diffuse irradiance and the non-lambertian properties of the panel cause the radiance received by a radiometer to be dependent on the solar zenith angle also, but in a considerably different manner than for the direct-irradiance case. Therefore, $R(0°/\theta)$ determined for direct irradiance will not account completely for the diffuse component, and R_t, determined under total irradiance conditions, will be in error.

The magnitude of the error caused by the nonisotropic diffuse irradiance on reflectance-factor measurements is difficult to evaluate. The results of Robinson and Biehl (1979), Kimes and Kirchner (1982), and Che et al. (1985) suggest that the error is larger for hazy than for clear atmospheric conditions, that it decreases with increasing wavelength, and that it is dependent on the solar zenith angle. For reference reflectance panels, we estimate the error to range from 0 to 3%, depending on the various conditions. Improved estimates of the error could be obtained from detailed studies using sophisticated atmospheric models to assess the nonisotropic nature of the diffuse component.

Concluding Remarks

The range of differences from the mean of seven measurements of $V(0°/\theta)$ for the pressed-halon standard was $\pm 0.2\%$ for incidence angles ranging from 20° to 70°. It is reasonable to assume that the same precision can be obtained for $V(0°/\theta)$ of the reference panels. Considering the various factors, it is our opinion that the accuracy of the method is on the order of 1%, although this is difficult to verify.

Major advantages of the technique for reference-panel calibration described here over conventional laboratory calibration methods are, first, that the irradiance and viewing geometry is the same as is used in field measurements and, second, that the equipment and facilities needed are available or can be constructed at many field research stations. Halon powder is commercially available, and the necessary tools to construct a pressed-halon standard can usually be obtained. A disadvantage of the technique is that the sky must be sufficiently cloud-free that sky irradiance changes are minimal during the measurement period. This requirement can be restrictive during long periods of cloudy weather.

Reflectance factors for panels constructed by the same person at the same time may differ. Panels constructed by different people following the same general procedure may differ considerably. Furthermore, the reflectance characteristics of a panel will change with use. It is evident that accurate field reflectance-factor data can only be obtained if calibrated reference panels are used. The results presented in this report demonstrate the need for careful panel calibration.

When precise reflectance-factor data are necessary, as in the case of in-flight calibration of satellite sensors, the effect of diffuse irradiance on reflectance-factor measurements should not be ignored.

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